The search for η'-bound nuclei in the LEPS2/BGOegg experiment

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1 Introduction

We started the LEPS2/BGOegg experiment in 2014. After a long time for analyses, the first paper from the LEPS2/BGOegg collaboration on the π^0 photoproduction was published in 2019 [1]. In this article, we report latest results on the η'-bound nuclei search in the LEPS2/BGOegg experiment.

An $\eta'(958)$ meson has a larger mass compared with other pseudoscalar mesons in the same nonet, π, K, η. According to Ref.[2, 3, 4], $U_A(1)$ anomaly plays an important role to explain the large η' mass. Several model calculations expect a large mass reduction of the η' mass in a nucleus [5, 6] where the effect of the $U_A(1)$ anomaly might be weakened together with the partial restoration of chiral symmetry [7, 8]. The mass reduction in a nucleus can be translated as an attractive potential between an η'-meson and a nucleus [9]. If the real part of the potential V_0 is deep enough and the imaginary part W_0 is small enough, the η' meson and the nucleus form a bound state. The NJL model and linear sigma model expect $V_0 = -150$ and –80 MeV, respectively [5, 6]. On the other hand, there are large uncertainties of V_0 evaluated from experiments [10, 11]. We searched for the η'-nucleus bound state using BGOegg detector system at LEPS2 in SPring-8.

2 Experiment

To search for the η'-nucleus bound state, we used missing-mass spectroscopy of the $^{12}\mathrm{C}(\gamma, p)$ reaction. Missing-mass spectroscopy around η'-mass suffers from numerous background arising from multiple light-meson productions. Thereby, we tagged an $\eta-$proton pair, which is expected to be emitted in the $\eta' N \to \eta N$ absorption process of a bound η'. More specifically, we investigated the following process:

$$\gamma + {}^{12}\mathrm{C} \to p_f + \eta' \otimes {}^{11}\mathrm{B} \tag{1a}$$

$$\hookrightarrow \eta' + p \to \eta + p_s. \tag{1b}$$

We carried out missing-mass spectroscopy by measuring the momentum of γ and forward going proton, p_f, with the tagging counter and the time-of-flight (TOF) wall made of resistive plate chambers (RPCs), respectively. We identified an η meson from the $\eta \to 2\gamma$ decay process using the BGOegg calorimeter. The side-going proton, p_s, is identified from the correlation of the energy deposit in BGOegg and inner plastic scintillators (IPSs), located inside BGOegg. Details of the experimental setup are described in Ref.[1].

3 Analysis

In Fig.1(a), we show the invariant mass distribution of 2γs detected with BGOegg. We see a clean peak of the η meson. The combinatorial background from multi-pion production is small as the number of events in the side band of the η peak is small. Fig.1(b) shows the excitation energy distribution of the $\gamma + {}^{12}\mathrm{C} \to p_f + (\eta + p_s) + \mathrm{X}$ reaction. The excitation energy is defined as:

$$E_{\mathrm{ex}} - E_0^{\eta'} = MM({}^{12}\mathrm{C}(\gamma, p_f)) - M_{^{11}\mathrm{B}} - M_{\eta'}, \tag{2}$$

where $MM({}^{12}\mathrm{C}(\gamma, p_f))$ is the missing mass in the $^{12}\mathrm{C}(\gamma, p_f)$ reaction, and $M_{^{11}\mathrm{B}}$ and $M_{\eta'}$ represent a mass of $^{11}\mathrm{B}$ and η', respectively. In Fig.1(b), there is no enhancement in $-50 < E_{\mathrm{ex}} - E_0^{\eta'} < 50$ MeV, where signals from the η'-bound states are expected. We investigated the observed events and found that most of them are background events coming from the $\gamma + {}^{12}\mathrm{C} \to p_f + \eta + {}^{11}\mathrm{B}$ and $\gamma + {}^{12}\mathrm{C} \to p_f + (\eta + \pi^0) + {}^{11}\mathrm{B}$ reactions. In these events, an η is produced in the primary reaction, and another proton, p_s, is kicked out by either a primary η, π^0, or p_f. We introduced kinematical selection cuts to suppress those background events. A bound η' is almost at rest, and thus, the $(\eta + p_s)$ pair is emitted in a close back-to-back relation, with an isotropic polar angle distribution. In contrast, most of the η and p_s from the background reactions are produced at forward angles. In addition, most of the $(\eta + \pi^0)$ events can be removed by requiring that there is no undetected π^0, namely, the missing energy, $E_{miss}^{\eta p_s p_f} = E_\gamma + M_{^{12}\mathrm{C}} - M_{^{11}\mathrm{B}} - E_\eta - E_{p_s} - E_{p_f} \lesssim M_{\pi^0}$. Here, E and M indicate the total energy and the mass of each particle, respectively. From above features, we determined the kinematical selection cuts to enhance signals as:

(a) the η-p_s opening angle : $\cos\theta_{lab}^{\eta p_s} < -0.9$,

(b) missing energy : $|E_{miss}^{\eta p_s p_f}| < 150$ MeV,

(c) the p_s polar angle : $\cos\theta_{lab}^{p_s} < 0.5$,

(d) the η polar angle : $\cos\theta_{lab}^{\eta} < 0$.

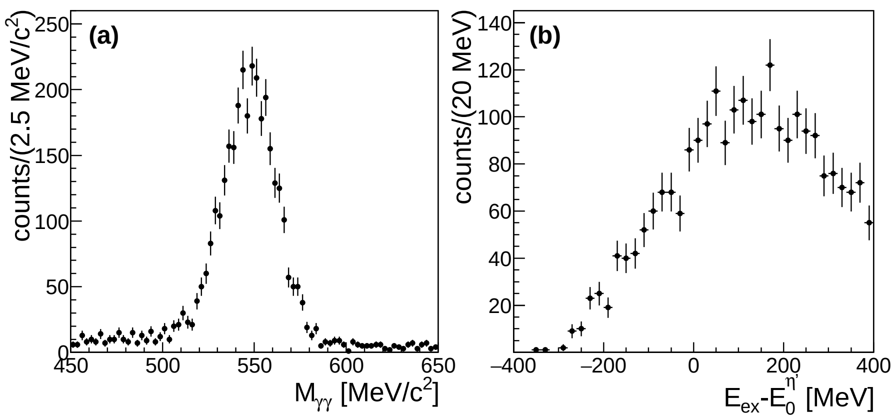

Figure 1: (a) The 2γ invariant mass distribution around the η mass and (b) the excitation function of the $(\eta + p_s)$ coincidence data.

4 Results

In Fig.2, we show the two dimensional plot of $\cos\theta_{lab}^{\eta}$ vs $E_{\rm ex} - E_0^{\eta'}$ after cuts (a)–(c). There is no event satisfying cut(d) in $-50 < E_{\rm ex} - E_0^{\eta'} < 50$ MeV, thus, we observe no $(\eta + p_s)$ events from η' absorption via the $\eta' N \to \eta N$ process. We obtained that the experimental upper limit of the production cross section of the η'-bound nuclei with an $(\eta + p_s)$ emission in $\cos\theta_{lab}^{\eta p_s} < -0.9$ is 2.2 nb/sr, at the 90% C.L..

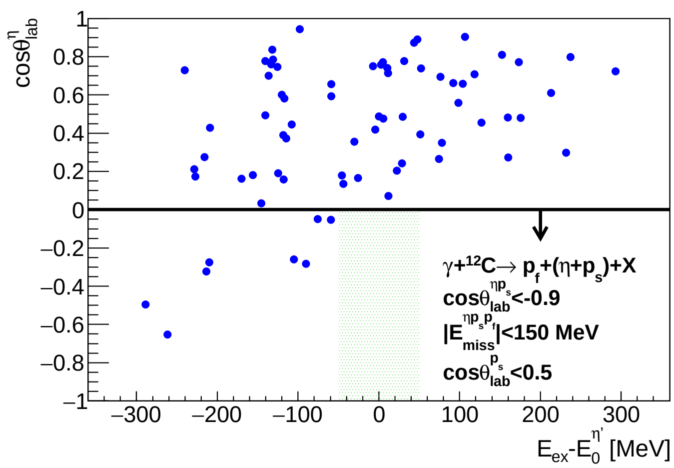

Figure 2: The two dimensional plot of $\cos\theta_{lab}^{\eta}$ vs $E_{\rm ex} - E_0^{\eta'}$ of the $(\eta + p_s)$ coincidence data after applying the kinematical cuts (a)–(c). The region to search for signals is shown with green hatching.

5 Discussion

We compared the obtained experimental upper limit of the production cross section with the theoretical expectation calculated in the framework of a distorted wave impulse approximation (DWIA) for $V_0 = -20$ and -100 MeV cases [12]. The theoretical expected cross section of the η'-bound nuclei with an $(\eta + p_s)$ emission is described as

$$\left(\frac{d\sigma}{d\Omega}\right)^{\eta+p_s}_{theory} = F \times \left(\frac{d\sigma}{d\Omega}\right)^{\eta' abs}_{theory} \times \mathrm{Br}_{\eta' N\to\eta N} \times P^{\eta p_s}_{srv}. \tag{3}$$

Here, F is the normalization factor of the absolute value of the theoretical cross section, $\mathrm{Br}_{\eta' N\to\eta N}$ the unknown branching fraction of the $\eta' N \to \eta N$ absorption process in all absorption processes, and $P^{\eta p_s}_{srv}$ the probability that an $(\eta + p_s)$ is emitted in $\cos\theta^{\eta p_s}_{lab} < -0.9$ from the $\eta' N \to \eta N$ reaction after the interaction in the nucleus. The cross section of the η' absorption mode, $\left(\frac{d\sigma}{d\Omega}\right)^{\eta' abs}_{theory}$, was calculated within a DWIA and it was obtained to be 79.7 and 292.2 nb/sr in $-50 < E_{\mathrm{ex}} - E^{\eta'}_0 < 50$ MeV for $V_0 = -20$ and -100 MeV, respectively. We evaluated F from the comparison of the experimental cross section of the $\gamma + {}^{12}\mathrm{C} \to p_f + \eta' + \mathrm{X}$ reaction and the theoretical cross section of the η' escape process. We derived $F = 0.38 \pm 0.10(\mathrm{stat}) \pm 0.03(\mathrm{syst})$ and $0.35 \pm 0.09(\mathrm{stat}) \pm 0.02(\mathrm{syst})$ for $V_0 = -20$ and -100 MeV, respectively. We derived $P^{\eta p_s}_{srv} = 12.1\%$ with the quantum molecular dynamics (QMD) transport model calculation [13]. The comparison of the experimental upper limit and theoretical expectation is shown in Fig.3 as a function of $\mathrm{Br}_{\eta' N\to\eta N}$. Our results indicate small $\mathrm{Br}_{\eta' N\to\eta N}$ and/or a shallow η'-nucleus potential V_0.

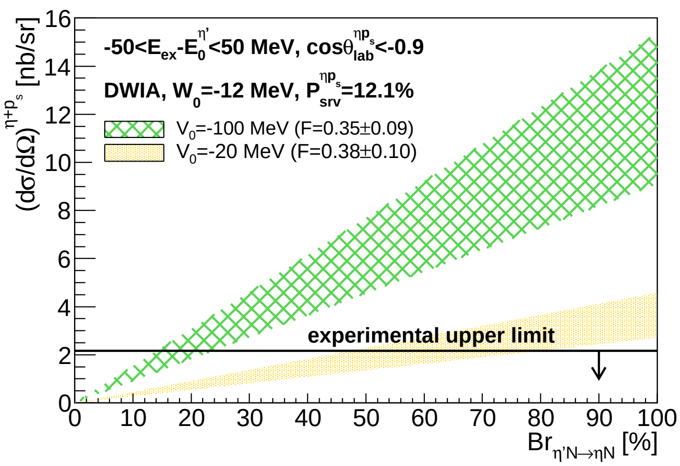

Figure 3: The comparison of the experimental upper limit of the production cross section of the η'-bound nuclei with an $(\eta + p_s)$ emission and the theoretical expectation for the case of $V_0 = -100$ and -20 MeV.

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